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ANALYSIS OF THERMAL BARRIER COATED PISTON FOR SI ENGINE APPLICATIONS

MANOJ BABU. A[1*], SARAVANAN. C. G[2] & RAJAN. K[3]

[1]*Research Scholar, Department of Mechanical Engineering, Annamalai University, Chidambaram, Tamil Nadu, India*

[2]*Professor, Department of Mechanical Engineering, Annamalai University, Chidambaram, Tamil Nadu, India*

[3]*Professor, Department of Mechanical Engineering, Dr. MGR Educational and Research Institute, Chennai, Tamil Nadu, India*

ABSTRACT

The efficiency of any internal combustion engine depends upon the heat energy available for combustion. In this paper, a theoretical analysis was carried out on both uncoated and coated piston to find the temperature distribution over the piston length. Even though many coating materials are available and they have their own advantage and disadvantage, in this work, Alumina has been taken based on the literature. Also the analysis was carried out with various coating thicknesses such as 60, 70,80, 90 and 100 microns. It is found that a drastic difference was found in between uncoated and coated piston. The coated piston showed very high thermal barrier capability than uncoated piston. Also the coating thickness does not produce much impact on thermal capability. But since the higher level of thermal coating will lead to increase of chamber temperature, it may lead to knocking of an engine. Hence, an optimum thickness of 100 microns was considered suitable for SI engine applications.

KEYWORDS: TBC, Coating Material, Coating Thickness & Temperature Distribution

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Original Article

1. INTRODUCTION

The performance of an internal combustion engine are evaluated by its thermal property “BRAKE THERMAL EFFICIENCY”. In the same time, due to stringent emission norms, the automotive manufacturers are forced to manufacture an engine with very less emission. Hence, in order to achieve a good thermal efficiency and less emission, various techniques are followed. Among those techniques, one of the prominent methods is TBC technique. TBC can be applied for both diesel and petrol engines. But very few literatures are found about the application of TBC in SI engines. It is found from the literature that TBC can significantly improve the performance of a diesel engine (1-6). Also the TBC technique can be used in diesel engines along with Nanobiofuel (1-2). An evidence is available in the literature that TBC will reduce the emission levels (2-3) and it will significantly reduce the thermal stress of a piston(4).

The TBC technique is widely used in petrol engines also (7-17). The coating can be applied inside the combustion chamber, piston body, piston rings and valves. There are various materials are available for coating over the piston (1-3,4-5,7-9,11-12,14-15). From the literature, it was found that every material have their unique properties and their advantages and disadvantages j(15). Hence, it is reliable to select the coating material according to the requirement and the temperature applied. It was found that stabilized zirconia coating on the piston of a SI engine has lowered the substrate temperature of the piston when compared to the uncoated piston. This indicates that stabilized zirconia coating will reduce the thermal damage of the piston and it will protect the piston from

thermal fatigue (7). Also it was reported from the literature that when Y-PSZ and Mg-PSZ coating will increase the surface temperature of the piston in the coated region. This has improved the emission and also it was concluded that Y-PSZ coating is better than Mg-PS2 coating (9). Experiment proved that alumina coating will increase the thermal efficiency well and reduce the mass of fuel consumption and as well as brake specific fuel consumption (14, 17). Also it was reported that the cold start hydro carbon emission will be considerably reduced when compared to the standard engine when TBC is applied (12).

The thickness of the TBC are very important factor to decide the performance of an internal combustion engine. The coating thickness can be applied from 0.03mm to 1.5mm. The FEA analytical result proved that 0.1 to 1.5mm coating is optimum for diesel engine applications (6). Temperature distribution is the function of thickness of coating (8). It was observed that with the increasing thickness, the surface temperature of the coating is increased (10). The thinner coating found to produce more compressive stress than the thicker coatings. Also the thinner coating is found to produce more compressive Stress which may lead to crack propagation (13). But conversely, it was also reported that the thickness of a TBC does not produce any significant effect as far as the piston thermal state is concerned.

By considering the above literature review, a numerical analysis was conducted on an aluminium alloy piston with Al_2O_3 thermal coating with various coating thicknesses from 0.06 mm to 0.1mm. The alumina was selected due to its properties such as high corrosion resistance, high hardness and low oxygen-transparent. As the thin thickness coating will increase the thermal fatigue and very high thickness will not have much impact on thermal properties, an optimum coating thickness was selected in between 60 microns to 100 microns. The coating was applied on the piston crown area only. Also it was found from the literature that Al_2O_3 is better choice compared with other TBC materials for SI engine applications.

2. THEORETICAL ANALYSIS

A thermal analysis at steady state was conducted on a coated and uncoated piston to estimate the temperature gradients using a commercial finite element analysis software called ANSYS. A piston was drawn using the software CATIA. Then the image was imported to ANSYS. The dimension of the piston is given in Table 1. During the modelling of the piston, the surfaces of the piston was considered as adiabatic and the materials of coatings were considered as uniform and homogeneous. A 7999 element has been used in the FEA analysis. The number of nodes during the thermal analysis was 25997.

Table 1: Specifications of Piston

Description	Dimension
Piston diameter	73.72
Piston height	41.32
1st ring thickness	4.62
2nd ring thickness	4.22
3rd ring thickness	3.12

In thermal analysis, the base temperature for the both coated and uncoated piston was 600°C. The convective heat transfer coefficient was taken as 1500 W/m^2K. The boundary conditions for the piston analysis was obtained from the literature and also it was determined by author’s experience.

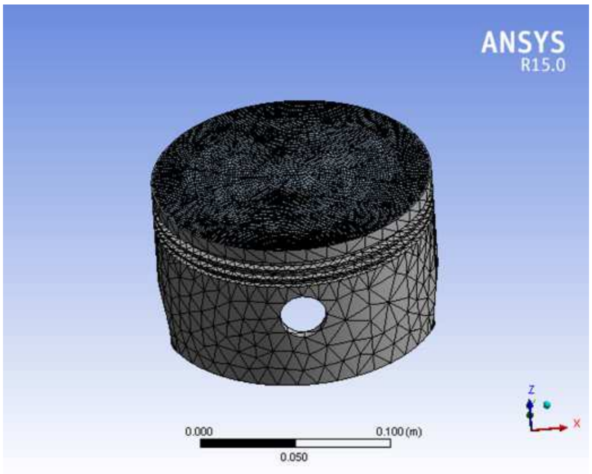

Figure 1: Meshed Piston Model.

The theoretical analysis was done with uncoated piston with the above said temperature and boundary conditions. Then the analysis was done with coated piston. Also the analysis was carried out by varying variable coating thickness. The thickness was considered as 60 microns, 70 microns, 80 microns, 90 microns and 100 microns. The piston material was considered as aluminium alloy under the coating material of alumina, Al_2O_3. This coating material was selected due to its properties such as low thermal conductivity, high corrosion resistant, high hardness and not oxygen transparent. During analysis for a coated Piston, a layer of 0.5 mm thickness has been removed from the top of the uncoated Standard piston. Then, an alumina coating was applied on the top surface of the standard piston. The meshing part of the piston is shown in figure 1. Then the appropriate boundary conditions were applied to get the temperature distribution over the entire length of the piston.

3. TBC MATERIAL

There are limited materials that are available for the coating of thermal barrier. Some of the materials are Yttria stabilized zirconia, Mullite, Alumina (Al_2O_3), AlSi, NiCrAl, Mg-PSZ, $CaZro_3$ etc… The expected properties of a TBC materials are (1) Good chemical stability (2) Resistance to higher temperatures (3) Supreme hardness values (4) Low densities (5) Very Low thermal conductivity (6) Low heat conduction coefficients and (7) High strength of compression. From the literature, it is found that every materials possess different properties as their advantages and disadvantages. The YSZ having the advantages of higher thermal expansion coefficient, lower thermal conductivity and higher thermal shock resistance. But conversely, it has the limitations such as sintering, phase transformation, property of corrosion and oxygen-transparent. Mullite has the advantages of corrosion-resistance, lower value of thermal conductivity, thermal shock resistance. But, it has the limitation of crystallization and lower value of thermal coefficient expansion.

Alumina is preferred as the good material for TBC for its some of the good heat retaining properties. It has the advantage of higher hardness and high strength, lower value of thermal conductivity, higher values of corrosion resistance and no oxygen transparent. Even though it has some disadvantages such as phase transformation, lower values of expansion coefficients, it is preferred as best coating material. Alumina is a very well-known ceramic material which has good thermal properties. The properties alumina is given in Table 2.

Table 2: Properties of Alumina

Composition	Al_2O_3
Purity	Alumina 99.9%
Density	3.9 gm/cc
Melting point	2015°C
Specific heat at 100°C	930 J / kg K
Thermal conductivity	40 W/mK at 20°C
Thermal shock index	0.2
Thermal cycle index	0.8
Flexural strength	380 MPa
Hardness HV	1500 kg f / mm^2
Tensile strength	262 MPa
Poison ratio	0.26
Young's modulus	370 GPa
Co-efficient of thermal expansion	8 µm / m °C

4. RESULTS AND DISCUSSIONS

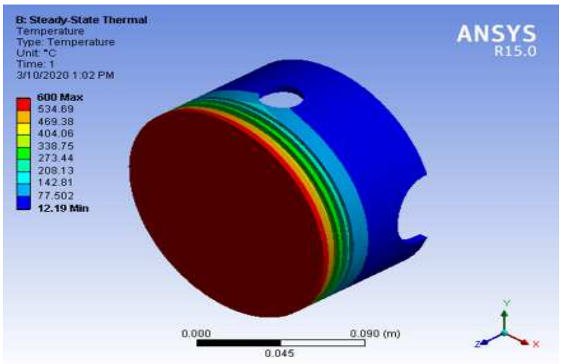

Figure 2: Uncoated Piston.

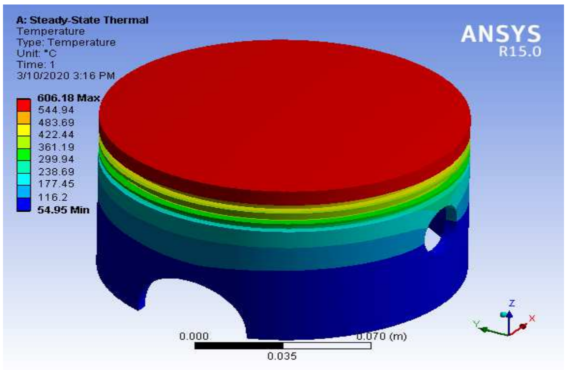

Figure 3: Coated Piston (100 microns).

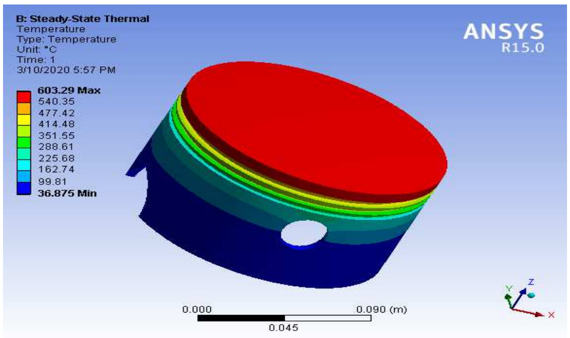

Figure 4: Coated Piston (90 microns).

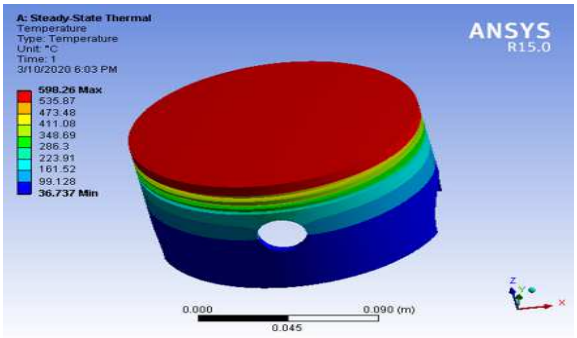

Figure 5: Coated Piston (80 microns).

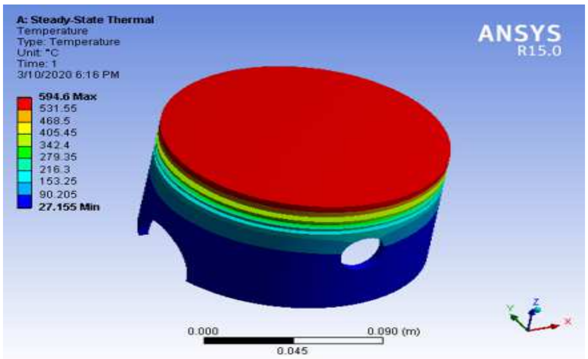

Figure 6: Coated Piston (70 microns).

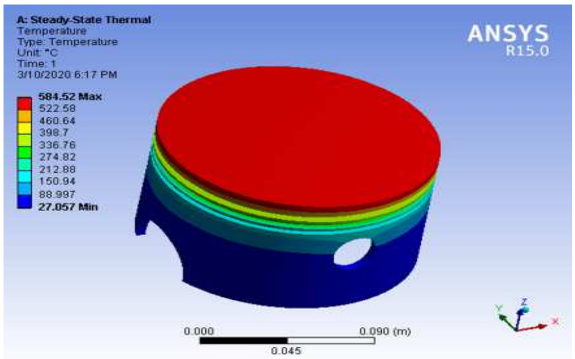

Figure 7: Coated Piston (60 microns).

The theoretical analysis was performed to evaluate the various temperature gradients on the conventional and TBC coated piston. The various temperature distributions and temperature contours of uncoated piston and coated piston of various thicknesses have been shown in figure 3 to 8.

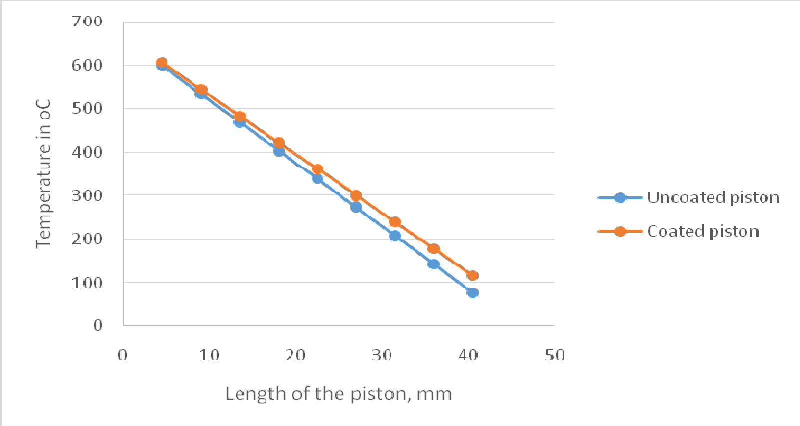

Figure 8: Temperature Distribution with Length of the Piston.

Figure 2 shows the temperature distribution of uncoated piston and figure 3 to 7 show the temperature distribution of the coated piston with varying coating thicknesses. From figure 8, it is found that the coated piston retains more heat than the uncoated piston. This is quite obvious that in standard uncoated piston, whatever temperature is produced or generated in the top of the Piston most of the heat is absorbed by the piston material itself. Hence due to this, the prevailing temperature which is available for the effective combustion is less in standard piston. Due to the above fact, the thermal efficiency of the engine is reduced and due to poor combustion, it leads to some emissions such as CO and Hydrocarbons. In order to avoid this, the coating is given on the Piston area to restrict the flow of heat to piston and other parts of an engine.

From figure 9, it is found that the top surface of the coated piston with 100 microns thickness retains high temperature at the top surface when compared to the lower portion of the piston than all thickness and uncoated piston. This is due to the fact that the TBC will eventually restrict the flow of heat from the top surface of the Piston to the lower side of the piston.

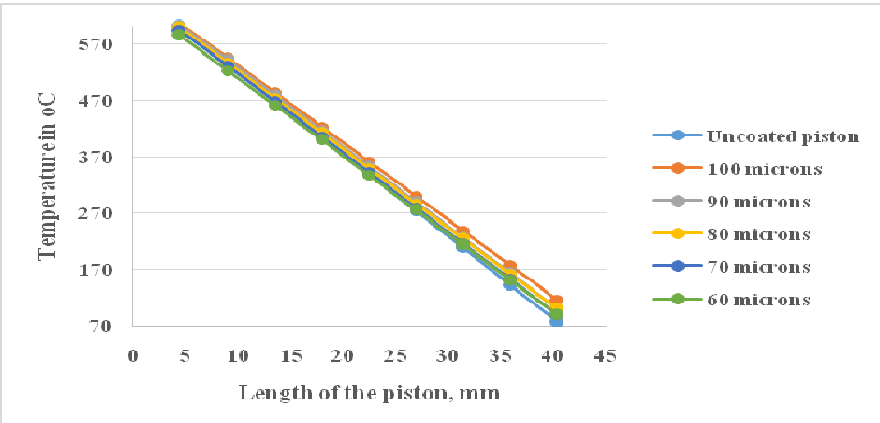

Figure 9: Temperature Distribution with Coating Thickness.

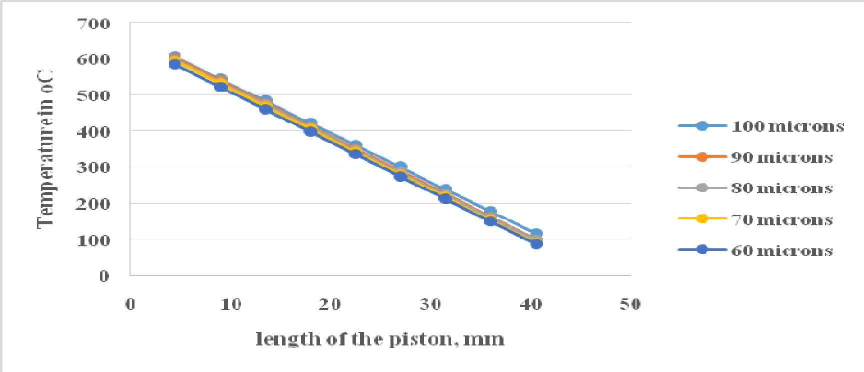

Figure 10: Temperature Distribution among Coating Thickness.

Also, it can be noted that as far as the coated piston is considered, a small temperature change is found with respect to varying thickness. It is observed that the 100 microns coating is superior to all other coatings. The temperature gradient is observed more in 100 microns coating thickness when compared to others.

But in the same time, from figure 10, it must be noted from the result that, the thickness does not have major effect on performance. This is agreed with the literature (15). As far as SI engine is concerned, the higher wall temperature will initiate knock, which can occur due to the auto ignition temperature of the air fuel mixture. Hence, less insulation has to be used to avoid very high engine wall temperature (15). Hence, engine should be sub- adiabatic but not fully adiabatic. Hence, due to this, 100 microns coating is preferred among the all coating thicknesses. Hence, if the coating thickness is further increased, there may be a possibility of knocking and engine will require special cooling system which will increase the weight and cost of the engine.

When comparing fig 2 and 3, it clearly indicate the role of Alumina coating over the top surface of the piston. There are many other coating materials are commercially available. But every material have their own advantages and limitations. But from the literature, it was found thatAl_20_3 is the best and better choice when compared to other materials as far as SI engine is concerned. Fig. 8 clearly indicates the differences in higher temperature between the coated and uncoated piston.

5. CONCLUSIONS

It is concluded from the theoretical analysis that the thermal barrier Coatings are doing a vital role in increasing the thermal efficiency of an engine which results in lower emission. Hence, a high hardness and high corrosion resistance material is required as coating material. Even though the aluminium metal have some limitations, it is found to be suitable for SI engine applications when it is used in the form of Aluminium oxide (Al_2O_3) which acts like a ceramic material. This will restrict the flow of heat through the other parts of the piston. Hence Alumina can be taken as best material for TBC. As far as the thickness is concerned, the thickness does not produce much difference in effect on Thermal efficiency. But higher level of insulation in SI engine may lead to knocking. Hence, optimum thickness is essential while selecting a thickness. Hence, it is concluded that Alumina coating with 100 microns thickness will considerably increase the thermal efficiency of the whole system and consequently it will reduce the amount of emission.

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